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ELECTRICAL FEEDBACK DETECTION SYSTEM FOR MULTI-POINT PROBES

The present invention generally relates to an electrical feedback detection system for detecting physical contact and/or close proximity between a multi-point probe and an locally electrically conducting, semi-conducting or super-conducting material test sample surface and further relates to the technique of controlling the relative position of a multi-point probe and a material test sample surface, and in particular to an electrical feedback detection system for the multi-point probe and multi-point testing apparatus described in European Patent Application EP 98610023.8 (Petersen), International Patent Application PCT/DK99/00391 (Capres ApS et al), European Patent Application EP 99932677.0 (Capres ApS), European Patent Application EP 99610052.5 (Petersen et al), and International Patent Application PCT/DK00/00513 (Capres Aps et al).

15 Description of the related art

A scanning tunneling microscope involving controlled approach of a single tip electrode towards a conducting sample surface is well known from the literature; see for example Binnig and Rohrer, *Scanning tunneling microscopy*, *Helv. Phys. Acta*, vol. 55, pg. 355 (1982). The scanning tunneling microscope consists of a conducting sample and tip, as shown in figure 1(a). If the tip and the sample are separated by a very short distance d and a potential V exists between them, a tunneling current

$$I \propto e^{-\sqrt{\phi}d},$$

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is running between the tip and sample, ϕ being the average work function of the materials. If the distance d is on the order of 1nm, a detectable current can be generated. Figure 1(b) shows a schematic of a complete scanning tunneling apparatus capable of positioning the tip within tunneling distance from the test sample at different test locations, thereby generating maps of nanometer scale topographic and electrical features of the test sample.

Figure 2(a)-(b) shows a schematic of the conventional four-point probe (see for example S.M. Sze, Semiconductor devices – Physics and Technology, Wiley New York (1985), and published international patent application WO 94/11745). The conventional four-point probe consists of four electrodes in an in-line configuration as shown in figure 2(a). By applying a current to the two peripheral electrodes, a voltage can be measured between the inner two electrodes. This allows the electric sheet resistivity of a test sample to be determined through the equation

$$\rho = c \cdot (V/I),$$

wherein V is the measured voltage and I is the applied current and wherein c is a geometry factor determined by the electrode separation of the four-point probe and the dimensions of the test sample. A principle diagram of the electronic circuit connected to the four-point probe is shown in figure 2(b).

Figure 3(a)-(b) shows a schematic of a conventional microscopic multi-point probe (see for example published European patent application EP 1 085 327 A1). Figure 3(a) shows the multi-point probe, consisting of a supporting body and a multitude of conductive probe arms freely extending from the base of the supporting body. Figure 3(b) shows a multi-point testing apparatus that implement the mechanical

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and electrical means for using the microscopic multi-point probe for measuring the electric properties of a test sample.

An object of the present invention is to provide a novel electrical detector mechanism allowing the detection of physical or otherwise electrical contact

5 between a multi-point probe and a sample test material surface.

A particular advantage of the present invention is related to the fact that the novel electrical detector mechanism allows the detection of electrical connection between a multitude of multi-point probe electrodes, thereby giving information of the electrical contact of a multitude of electrodes of the multi-point probe.

10 A particular feature of the present invention is that the novel electrical detector mechanism does not require a macroscopically conducting sample surface, thereby providing detection of electrical contact to any material surface that contains a local electrical path between several electrodes of the multi-point probe at a specific location of the multi-point probe.

15 The above object, the above advantage and the above feature together with numerous other advantages and features which will be evident from the below detailed description of a preferred embodiment of the present invention is according to the present invention obtained by a electrical feedback control system for detecting electrical contact to a specific location of a test sample, comprising:

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(a) Electric generator means connected to a first multitude of electrodes of a multipoint probe;

(b) A second multitude of switched impedance detection elements connecting said first multitude of electrodes of said multipoint probe; and

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(c) Electrical detector means for detecting a measuring signal from the electrical signal across said second multitude of switched impedance detection elements.

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The technique characteristic of the present invention of detecting contact between a multi-point probe and the test locations of a test sample by utilizing an electrical signal flowing in the multi-point probe electrodes avoids the use of laser deflection detection mechanisms in the case of microscopic cantilever based multi-point electrodes, which is a dramatic simplification of the conventional optical feedback control systems for microscopic cantilever based testing apparatus such as Atomic Force Microscopes and Scanning Resistance Microscopes.

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The electric generator means connected to a first multitude of multi-point probe electrodes according to the present invention sends a generator signal through the test sample at the test location, that being current or voltage, pulsed signal or signals, DC or AC having sinusoidal, square, triangle signal content or combinations thereof, ranging from LF to HF, in accordance with specific detection requirements such as sensitivity to resistance, inductance, capacitance or combinations thereof, having a LF sinusoidal AC current signal as the presently preferred embodiment.

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The first multitude of electrodes of a multi-point probe according to the present invention ranges from at least two electrodes to 64 electrodes, having the two peripherally positioned electrodes of the multi-point probe as the present preferred embodiment. Application of a generator signal to two peripherally positioned electrodes of the multi-point probe provides a resultant detector signal over the second multitude of impedance detection elements according to the present

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invention, and infers information about the electrical contact conditions of a third multitude of the multi-point probe electrodes. An electrical contact condition can involve physical contact, tunneling proximity, intermediate fluid meniscus, or any other effect allowing electrical current to flow between the multi-point probe electrodes and the test sample.

The second multitude of switched impedance detection elements according to the present invention ranges from one to ten, having three as the present preferred embodiment. The nominal values of the resistive part of the impedance detection elements ranges from $1\text{m}\Omega$ to $100\text{G}\Omega$, having $1\text{k}\Omega$, $10\text{k}\Omega$ and $100\text{k}\Omega$ as the presently preferred embodiment.

The electrical detector means measures an electrical signal across the second multitude of impedance detection elements according to the present invention, having a sensitive electrometer connected to a phase-locked lock-in amplifier as the preferred embodiment.

15 **Brief description of the drawings**

Additional objects and features of the present invention will be more readily apparent from the following detailed description and appended claims taken in conjunction with the drawings, in which:

20 Fig. 1(a)-(b), provides an overall illustration of the conventional scanning tunneling microscope. (a), a schematic of the tunneling region between a conducting tip and a test sample. (b), a view schematically showing a conventional scanning tunneling apparatus;

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Fig. 2(a)-(b), provides a schematic illustration of the conventional four-point probe.

(a), shows a schematic of a conventional four-point probe in electrical contact with a test sample. (b), shows an electrical schematic of a current source and electrometer connected to a conventional four-point probe;

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Fig. 3(a)-(b), shows an overall illustration of the conventional multi-point probe and testing apparatus. (a), shows the multi-point probe electrodes. (b), is a schematic of the multi-point testing apparatus;

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Fig. 4, shows a schematic view of the electrical feedback detection system according to the present invention;

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Fig. 5(a)-(b), shows an embodiment of the electrical feedback detection system according to the present invention, in which a multi-point probe is not electrically connected a test sample. (a), shows the detailed electrical configuration of the electrical feedback detection system. (b), shows the equivalent electrical diagram of the system;

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Fig. 6(a)-(b), shows an embodiment of the electrical feedback detection system according to the present invention, in which a multi-point probe is in electrical contact with a test sample. (a), shows the detailed electrical configuration of the electrical feedback detection system. (b), shows the equivalent electrical diagram of the system;

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Fig. 7(a)-(b), shows embodiments of the electrical feedback detection system according to the present invention in which the feedback detection system includes a generator of constant electrical current. (a), shows a single switched impedance detection element in the control circuit. (b), shows a multitude of switched impedance detection elements in the control circuit;

Fig. 8, shows an embodiment of the electrical feedback detection system according to the present invention in which the feedback detection system includes a generator of constant electrical current, and the detector signal is measured between a multitude of the multi-probe electrodes and the test sample material;

Detailed description of the preferred embodiments

A preferred embodiment is directed towards making an electrical feedback detection system for a multi-point probe and is described with respect to figures 4-8.

Figure 4 shows a schematic of a multi-point testing apparatus 100 employing an electrical feedback detection system. The apparatus consists of a multi-point probe 102 in proximity to a test sample 104 which can be moved by a motor stage 108 by means of a controller 106. The peripherally positioned electrodes of the multi-point probe is connected to an electrical feedback detection system 110, which is capable of determining if the multi-probe 102 is in electrical contact with the test sample 104. A detector signal 112 is provided from the electrical feedback detection system 110 to the controller 106, to enable a controlled positioning and measurement with the multi-point probe 102 at test locations on the test sample 104.

Figure 5(a)-(b) and 6(a)-(b) together shows the principle of a preferred embodiment of the present invention. Figure 5(a)-(b) shows a principle of the electrical

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configuration of the electrical feedback detection system 300 according to the invention, in a situation where no electrical contact exists between the multi-point probe 302 and the test sample 304. An electrical generator means generates a constant electrical current I_c , and is connected to the peripheral electrodes 302a and 302b of the multi-point probe 302. A impedance detection element consisting of resistive detection element R is connected to the circuit through closed switch SW , and the electrical potential V_r across the resistive detection element R is measured by amplifier circuit A . The equivalent electrical diagram of feedback detection system according to the invention in the situation depicted in figure 5(a), is shown in figure 5(b). The constant current I_c runs through the resistive detection element R , thereby generating a potential difference

$$V_r = R \cdot I_c$$

Which is measured by amplifier A , and presented at the output of the feedback detection system. Figure 6(a)-(b) shows a schematic diagram and equivalent circuit of the feedback detection system 500 in the case where the multipoint probe 502 is in electrical contact with the surface of the test sample 504. The electrical generator means is connected to the peripherally positioned electrodes 502a and 502b of the multi-point probe 502. A generated current I_c flows in part through the closed switch SW and the resistive detection element R and the corresponding electrical potential V_r is measured by the amplifier circuit A , and in part through the test sample 504 represented by unknown resistive element R_x . In this case the potential difference V_r is

$$V_r = (R \cdot R_x) / (R + R_x) \cdot I_c$$

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With reference to figures 5 and 6 it is thus established that the introduction of electrical contact between a multi-point probe and a test sample generates a well-defined change in the output of the feedback detection system, hence allowing the detection of changes in the contact condition of a multi-point probe and a test sample.

In a preferred embodiment of the present invention the constant current generated by an electric generator means I_c is $1\mu\text{A}$ and the resistive detection element R has nominal value $100\text{k}\Omega$, and hence the detector signal V_r is 10V if no electrical contact is established between the multi-point probe and the test sample. If electrical contact exists to the test sample, the electrical properties of the test sample give rise to an effective resistance R_x of the test sample. The following table shows the resulting detector signal V_r for a range of different effective resistance values R_x for the test sample:

R_x	V_r	Relative change in V_r from situation of no electrical contact
10Ω	$9.99\mu\text{V}$	1,100,000
$10\text{k}\Omega$	9.99mV	1,100
$1\text{M}\Omega$	909mV	11
$100\text{M}\Omega$	9.09V	1.1

This shows that the electrical feedback detection system is in this particular preferred embodiment of the present invention able to detect contact to test samples with effective electrical resistances in the range from 10Ω to $100\text{M}\Omega$. In a preferred embodiment of the present invention the detector signal is used by the controller of

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a multi-point testing apparatus to determine the electrical contact condition of a multi-point probe to a test location of a test sample, and to actively change the contact condition by means of electrical signals to a motor stage defining the relative position of the multi-point probe and the test sample.

- 5 Figure 7(a)-(b) shows detailed implementations of preferred embodiments of the present invention. In figure 7(a), an electrical feedback detection system according to the invention 700 has the peripherally positioned electrodes 702a and 702b of a multi-point probe 702 connected to a differential voltage to current converter consisting of amplifier G, resistive detection element R_{set} and voltage follower A1.
- 10 The resistive detection element R is connected to the output of the voltage to current converter through switch SW. The output of the voltage to current converter is proportional to the voltage difference $V_1 - V_2$. The detector signal V_r is measured by means of amplifier A2. The current I_c from the voltage to current converter is sent through the closed switch SW and the resistive detection element R and through the
- 15 unknown effective resistance R_x in the test sample 704. Figure 7(b) shows an electrical feedback detection system according to the invention 800 with multi-point probe 802 connected to test sample 804 and electrical feedback detection circuit connected to the peripheral electrodes 802a and 802b of the multi-point probe 802. The electrical feedback detection circuit contains a multitude of resistive detection
- 20 elements R_1 and R_2 , which can be individually switched into the signal path of the electric generator means by means of switch SW, preferable application having three said resistive detection elements with nominal values in the range 100Ω to $10M\Omega$.
- Figure 8 shows another preferred embodiment of an electrical feedback detection
- 25 system according to the present invention 1000, with multi-point probe 1002

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connected to test sample **1004** and electrical feedback detection circuit connected between the peripheral electrodes **1002a** and **1002b** of the multi-point probe **1002**, and test sample **1004**. The generated current I_e runs in part through the test sample **1004**, and this gives rise to a change in detector signal V_r across a resistive

5 detection element **R**, even when only one of the multitude of multi-point probe electrodes is in electrical contact with the test sample.